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TEARES: toroidal energy- and angle-resolving electron spectrometer—results, recent modifications and instrument performance

M.R.F. Siggel-King [a, *], R. Lindsay [a, b], T.J. Reddish [c], D.P. Seccombe [c], F.M. Quinn [a]

[a] *Daresbury Laboratory, Daresbury, Warrington WA4 4AD, UK*
[b] *Institut de Ciéncia de Materials de Barcelona (CSIC), Campus UAB, 08193 Bellaterra, Spain*
[c] *University of Windsor, Department of Physics, Windsor, Ont., Canada N9B 3P4*

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Abstract

The toroidal energy- and angle-resolving electron spectrometer (TEARES) is a state-of-the-art instrument, which enables both the energy and angle of ejection of an electron to be measured simultaneously. First synchrotron results from TEARES are presented in this progress report. Relative cross-sections and asymmetry parameters for the Argon $3s3p^6 4p\ {}^1P_1^\circ$ 'window' resonance region have been measured; the results are in good agreement with the previously published data of Codling et al. In addition, significant modifications have been made to the spectrometer, which have greatly enhanced its performance. The reasons for these changes and their resulting effects on the data are presented.

Keywords: Charged particle optics; Toroidal analyser; Angular distribution; Photoemission

1. Introduction

Continuous development of synchrotron radiation facilities has lead to large improvements in the quality and quantity of radiation delivered to experimentalists. In some fields this progress has not been mirrored by comparable progress in detector technology, which is equally important to improving synchrotron radiation-based studies. Innovative instrumentation can yield improvements of many orders of magnitude in the speed and quality of information obtained. To this end, we are developing a toroidal energy- and angle-resolving electron spectrometer (TEARES), which has been designed to give a significant increase in the solid angle collection efficiency over the more conventional hemispherical or 127° sector analysers whilst preserving their energy- and angular-resolving properties.

2. Instrumental

The TEARES spectrometer comprises a toroidal electrostatic deflection analyser, together with appropriate entrance and exit lenses, and a two-dimensional electron detection system. This multi-purpose spectrometer has been designed to operate on various beamlines at the Synchrotron Radiation Source (SRS) at Daresbury and on third-generation sources, such as DIAMOND. A schematic of the electron optics of the spectrometer is shown in Fig. 1a, and a three-dimensional image of the toroidal analyser in Fig. 1b. Electrons are generated at the interaction region where the light and target (gas, in this case) intersect. These electrons are ejected in all possible radial directions; those travelling in a (horizontal) direction that is near perpendicular to the central axis of the spectrometer enter the double-focussing entrance lens. This lens focuses and transports the electrons on to the toroidal entrance slit. The toroidal analyser has a cylindrical radius of 120 mm, a spherical radius of 125 mm, a sector angle of 142.6° and an azimuthal angle of 270°. Electrons of a specified energy

* Corresponding author. Tel.: +44 1925 603571; fax: +44 1925 603124.
E-mail address: m.r.f.siggel-king@dl.ac.uk (M.R.F. Siggel-King).

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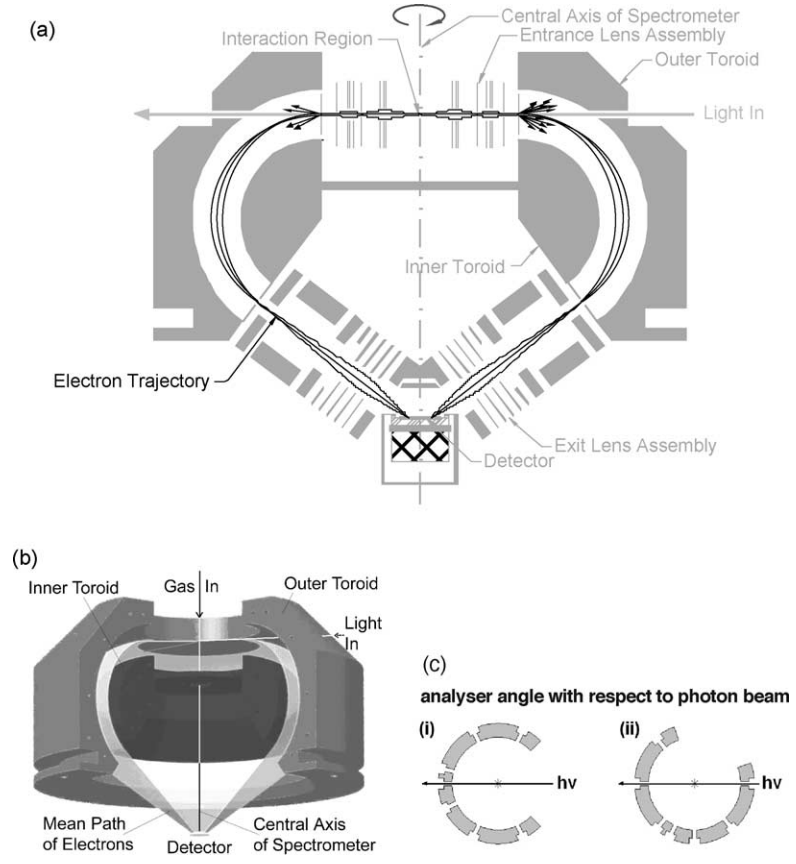

Fig. 1. (a) Schematic diagram of the electron optical components of TEARES. Trajectories for electrons of the same initial kinetic energy, but different polar angles, focused to the same point at the exit of the analyser are shown as black lines. Undesirable scattered electrons in the toroidal analyser that result from the synchrotron light hitting the toroidal entrance slits are shown as black lines with arrows. (b) A computer-generated 3D image of the TEARES toroidal electrostatic deflection analyser. The interaction region is at the intersection of the light and gas beams. (c) Cross-sectional views of the TEARES analyser showing the horizontal plane that contains the centre of the interaction region, the photon beam, and the main polarisation vector of the light. Two orientations of the spectrometer with respect to the photon beam propagation direction are shown. (i) 0°, which gives the lowest background. (ii) 295°.

traverse the toroidal deflector and are re-focused at its exit slit. The electrons then enter a four-element lens which focuses, demagnifies and transports them onto the detector. A commercially available Quantar fast-resistive-anode imaging detector is used to detect the electrons. The spectrometer rotates about its central axis (see Fig. 1a and b) to enable a choice of acceptance angles with respect to the propagation direction of the synchrotron light; two possible angular orientations are shown in Fig. 1c. A detailed description of the TEARES spectrometer has previously been published [1,2], and the design of toroidal analysers has been discussed in detail by Toffoletto et al. and by Reddish et al. [3,4]. In the experiments reported here, the gaseous target was an effusive gas-jet. The inlet needle was mounted vertically pointing downward, orthogonal to the synchrotron photon beam (see Fig. 1b).

The studies reported in this work were obtained using two beamlines at the SRS. The first study was undertaken on MPW6.1 [5], where the experimental chamber (at 10^{-5} Torr) was isolated from the UHV beamline (10^{-9} Torr) using a 1426 Å thick Magnesium window. The synchrotron beam focus was ∼160 mm short of the interaction region, due to beamline optics, resulting in a correspondingly larger-than-optimum spot size at the interaction region. The second study utilised low energy radiation from beamline 5D [6], where the experimental chamber was isolated from the UHV beamline using a Pyrex capillary of 1 mm inner diameter together with a differential pumping section. For unavoidable mechanical reasons it was necessary to terminate the capillary just before the light entered the chamber port and consequently the capillary end was ∼440 mm from the interaction region. Unfortunately, this resulted in a large (∼2 mm height × ∼4 mm width) synchrotron beam at the interaction region. The neon data presented here were obtained at a photon energy of 40 eV with a toroidal pass energy of 10 eV. These data have been normalised to an SRS ring current of 200 mA by monitoring a mesh diode placed just before the monochromator.

Two separate experimental runs were undertaken on 5D. The first utilised the TEARES instrument as described above and previously [2]. For the second run, several modifications to the spectrometer were made, which include: (1) increasing the heights of the analyser entrance aperture (from 1.00 mm to 2.00 mm), the analyser angle defining aperture (from 1.92 mm to 2.00 mm) and the entrance lens skimmer slit (from 1.46 mm to 2.97 mm), (2) extending the azimuthal

angle of the first entrance lens from 270° to 360° (the first three lens elements the electrons pass through), and (3) adding a mesh cylinder, of diameter 65 mm, around the interaction region. The reasons for these changes are discussed in the next section.

3. Results

3.1. Polarisation of the synchrotron light

The polarisation of the light can be determined from two angle-resolved spectra of different gasses, or transitions, provided (a) the asymmetry parameters, β, are known, (b) the kinetic energies, E, of the measured electrons (and hence analyser tuning) are the same, (c) the photon energy is similar (hence degree of polarisation, P, is the same), and (d) there are no significant higher order (non-dipole) contributions. The measured intensity at a given angle for a specific transition is given by:

$$I = A(E,\theta)\left(\frac{\sigma}{4\pi}\right)\left[1+\frac{\beta}{4}(1+3P\cos(2\theta))\right]$$

where $A(E, \theta)$ is the relative analyser efficiency for a given E and emission angle, σ the total cross-section for the transition at the measured photon energy and θ is the photoelectron ejection angle with respect to the major polarisation axis of the photon beam. If the above conditions are satisfied for two different transitions, the ratio of the two equations can then be taken and fitted to the ratio of the (background subtracted) data sets to obtain P, the polarisation of the light. Using this procedure with the Helium $1s^2 \rightarrow 1s$ and unresolved Argon $(3p)^6 \rightarrow (3p)^5$ transitions we have determined the polarisation of the light on MPW6 at ~26 eV to be 0.75 ± 0.03. This is in good agreement with the theoretical value expected from the optical beamline design of ~0.78.

3.2. Relative partial cross-section and asymmetry parameter measurements

To check the performance of the TEARES system, data was obtained in the Argon autoionising window resonance region associated with the excitation of an outer 3s electron to the first Rydberg orbital ($3s3p^6 4p\ ^1P_1^\circ$) at ~21 eV. Images of the angular distributions of the ejected photoelectrons were collected for a range of photon energies in the region of this resonance. These measurements were taken with the electron kinetic energy (E) set to the photoelectron peak maxima and with a toroidal pass energy of 25 eV. For each image, two associated background images were recorded at the same kinetic energy but with $h\nu = \pm 1$ eV. The 3-D images were converted to photoelectron yield versus θ plots from which were subtracted an average of the two background spectra. Relative cross-sections were obtained as a function of photon energy by normalising the sum of the counts at each angle to the integrated photon flux. The results of this procedure are shown in Fig. 2a where they are compared to the absolute values of Codling et al. [7]. Our relative data has been normalised to Codling's data at an arbitrary photon energy (26.52 eV) selected to be away from the resonance region. The shapes of the two data sets are in excellent agreement.

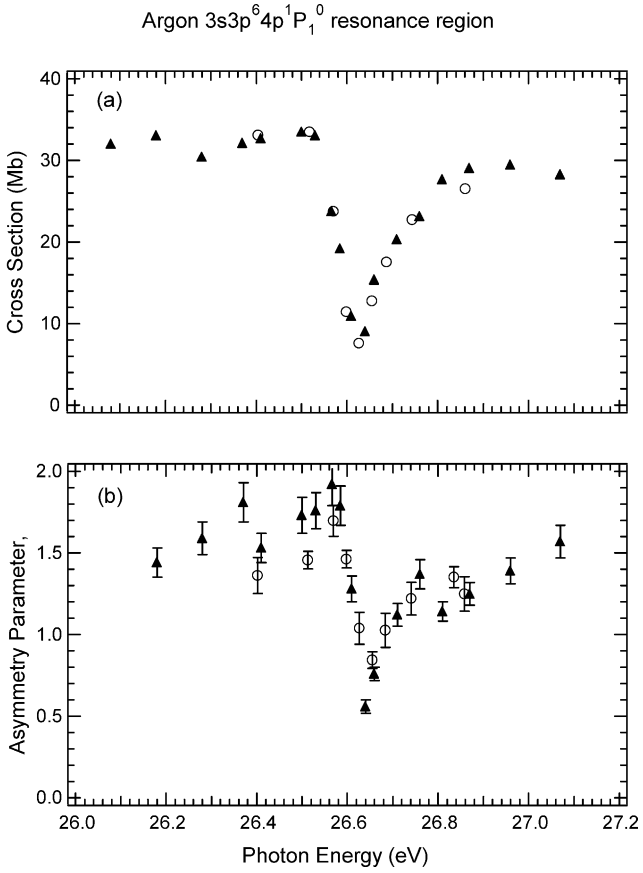

Fig. 2. Argon $3s3p^6 4p\ ^1P_1^\circ$ 'window' resonance region. (a) The measured cross-section values from Codling et al. [7] (open circles) are compared to those obtained in this study (solid triangles), normalised to those of Codling et al. at 26.52 eV. (b) Comparison of the corresponding asymmetry parameters obtained in this work (solid triangles) and those of Codling et al. [7] (open circles).

To extract β parameters [8], the angular response of the analyser $[A(E, \theta)]$ must be determined. This was done by recording a calibration image at an E similar to those used for a transition with a known β using the same analyser tuning. The angular response $[A(E, \theta)]$ is the ratio of the resulting angular distribution to the expected one. Once the argon data has been corrected for the angular efficiency variation, β may be obtained by fitting the angle-resolved data to:

$$C\left(1+\frac{\beta}{4}(1+3P\cos(2\theta))\right)$$

where C is a constant and P was taken to be 0.75 for all photon energies in this narrow resonance region. The resulting asymmetry parameters as a function of photon energy are shown in Fig. 2b together with the data of Codling et al. [7].

Our experimental measurements were made in the non-dipole plane, whilst those reported by Codling et al. were measured in the dipole plane [9]. We have assumed that non-dipole effects in the region of the argon window resonance are negligible, as the photon energy is relatively low, aware that occasionally this assumption is inappropriate [10]. If there are non-dipole effects in this region, they will have an effect upon the measured β values reported here. Their effect is, however, likely to be within our error bars, which are mainly due to uncertainties in the polarisation of the light. The good agreement shows that our instrument and methods are capable of measuring reliable angular distribution parameters. More accurate values would be obtainable if the system were operating on a modern undulator at a third generation source, where the polarisation is typically 0.99 ± 0.01 and the photon spot size is smaller.

3.3. *Effects of the finite size of the photon beam and field penetration from the entrance lens*

A sample spectrum of the unresolved Ne 2p doublet, obtained on beamline 5D during the first run is shown in Fig. 3a. The overall shape of the 2p peak is consistent with expectations. The relatively large constant background, often present in toroidal analysers, is due to the inability of the toroidal spectrometer to filter out unwanted (metal scattered) electrons in the azimuthal (horizontal, angle-resolved) dimension. In the present case, this problem is exacerbated by the relatively large photon beam at the interaction region.

The spectrum in Fig. 3a was obtained with appropriate voltages applied to the entrance lens elements to focus the electrons from the interaction region to the entrance of the toroidal analyser. The spectrum in Fig. 3b was obtained with the entrance lens elements grounded (the electrostatic equivalent of removing the entrance lens). Turning the entrance lens 'off' resulted in the peak width (fwhm) and signal intensity slightly decreasing, as expected; the peak has also shifted in observed kinetic energy, which was *not* expected. The observed shift in kinetic energy was determined to be due to 'asymmetric' electrostatic field penetration from the entrance lens into the interaction region, resulting in a non-zero potential at the target. The spectra in Fig. 3a and b were taken with the photon beam entering the spectrometer through the

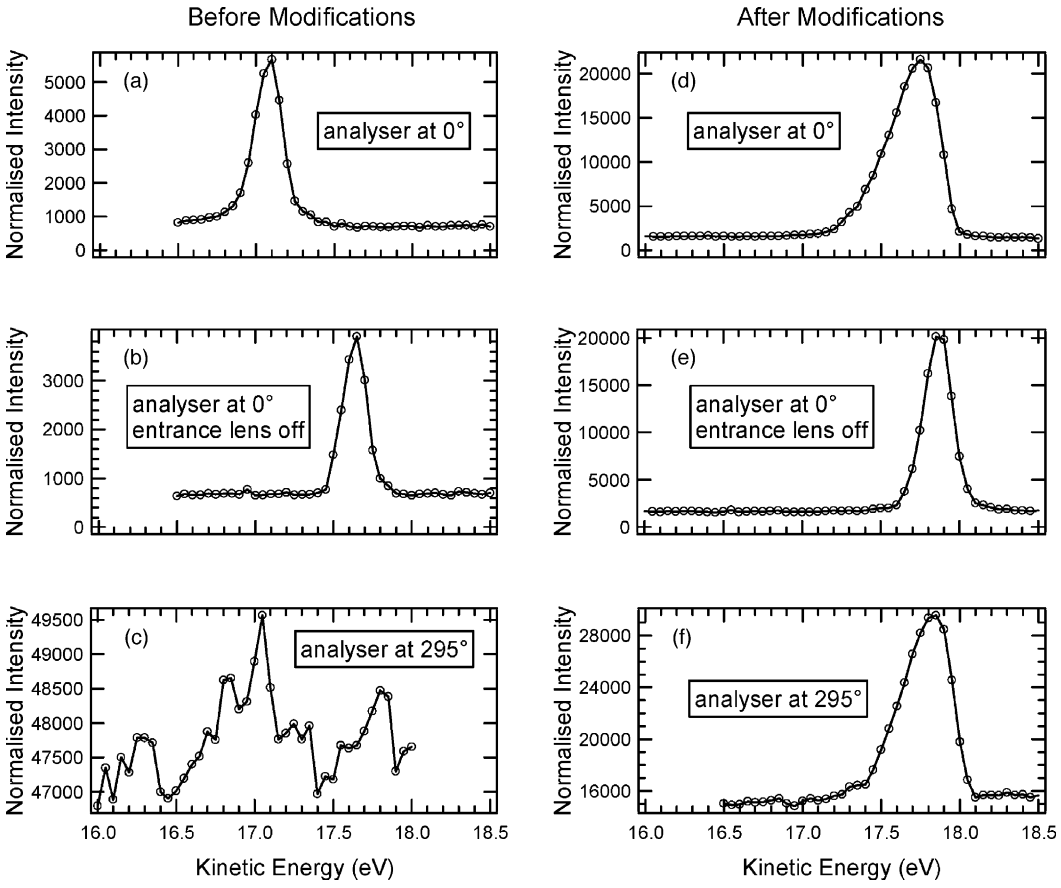

Fig. 3. Spectra of the unresolved Ne 2p doublet. All spectral intensities have been normalised to correspond to an SRS ring current of 200 mA; no attempt was made to account for the small differences in Neon pressure. The spectra in (a–c) and (d–f) were taken before and after, respectively, the modifications to TEARES. (a, d) Spectrometer configuration as in Fig. 1c(i) with the light entering through the 90° cut-out. (b, e) As in (a) but with the entrance lens elements grounded. (c, f) As in (a) but with the spectrometer configuration as in Fig. 1c(ii).

centre of the 90° cut-out and exiting through a 10 mm hole in the spectrometer, as shown in Fig. 1c(i). In order to fully utilise the TEARES spectrometer for future non-dipole parameter studies and surface science photoelectron diffraction experiments, the spectrometer needs to rotate so the photon beam enters the spectrometer through one of several 10 mm diameter holes. Fig. 3c shows a spectrum taken with the light entering and exiting through a pair of opposite 10 mm holes (see Fig. 1c(ii)). The peak (at ∼17.1 eV) can barely be seen above the background, which is due to electrons generated in the toroids when the wings of the relatively large photon beam hit the analyser entrance slits, as it both enters and exits the spectrometer (see Fig. 1a).

3.4. Effects on the spectra resulting from modifications of the instrument

Following the MPW6 run and the first 5D run, various modifications were made to the spectrometer, as described above. To test these changes, spectra in Fig. 3d–f were obtained under identical conditions to those used in Fig. 3a–c. Fig. 3d shows a spectrum of the unresolved Ne 2p doublet obtained with the light entering through the centre of the 90° cut-out of the spectrometer, as in Fig. 3a. The differences between the two spectra are as anticipated [11]; the count rate at the peak maximum and the signal-to-background-ratio have both increased.

Turning the entrance lens 'off' (Fig. 3e) results in an increase in resolution (peak narrowing) and the peak becoming more symmetric, as expected, due to the decrease in the angular acceptance of the analyser [11]. It is interesting to note that the count rates at the peak maximum and in the background are similar in Fig. 3d and e; the count rates in Fig. 3d are expected to be greater than in Fig. 3e. While the overall efficiency of the lenses still gives us cause for reflection, the signal-to-background ratio, i.e. the rejection of unwanted metal scattered electrons, has been substantially improved by these modifications.

A spectrum taken with the spectrometer rotated so the photon beam enters and exits through two opposite 10 mm holes is shown in Fig. 3f. A prominent peak is now observed. The shape and kinetic energy of the peak are similar to the peak in Fig. 3d, as expected. The counts in the peak at the peak maximum are about 30% less than in Fig. 3d. This may be due to spectrometer alignment with respect to the photon beam. The large decrease in the background relative to that shown in Fig. 3c, demonstrates the improved performance due to the spectrometer modifications.

4. Summary

We have shown that the TEARES spectrometer is capable of measuring relative partial cross-sections and angular distribution parameters. We have also substantially improved the performance of the instrument, opening the way for future experiments such as non-dipole studies, surface photoelectron diffraction measurements, and ultimately the possibility of "snap-shot" electron spectroscopy in real-time.

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References

[1] M.R.F. Siggel-King, R. Lindsay, F.M. Quinn, J.F. Pearson, G.W. Fraser, G. Thornton, American Institute of Physics Conference Proceedings, vol. 73, 2003, p. 937.
[2] M.R.F. Siggel-King, R. Lindsay, F.M. Quinn, J. Pearson, G. Fraser, G. Thornton, J. Electron Spectrosc. Relat. Phenom. 137–140 (2004) 721.
[3] F. Toffoletto, R.C.G. Leckey, J.D. Riley, Nucl. Instrum. Methods Phys. Res. B 12 (1985) 282.
[4] T.J. Reddish, G. Richmond, G.W. Bagley, J.P. Wightman, S. Cvejanović, Rev. Sci. Instrum. 68 (1997) 2685.
[5] M. Bowler, J.B. West, F.M. Quinn, D.M.P. Holland, B. Fell, P.A. Hatherly, I. Humphrey, W.R. Flavell, B. Hamilton, Surf. Rev. Lett. 9 (2002) 577.
[6] P. Finetti, D.M.P. Holland, C.J. Latimer, C. Binns, F.M. Quinn, M.A. Bowler, A.F. Grant, Nucl. Instrum. and Method B 184 (2001) 627.
[7] K. Codling, J.B. West, A.C. Parr, J.L. Dehmer, R.L. Stockbauer, J. Phys. B: Atom. Molec. Phys. 13 (1980) 693.
[8] J.P. Wightman, S. Cvejanović, T.J. Reddish, J. Electron Spectrosc. Relat. Phenom. 95 (1998) 203.
[9] The 'dipole plane' is perpendicular to the synchrotron light propagation direction. The so-called 'non-dipole plane' contains both the propagation direction and the electric field vector of the synchrotron light, and is physically close to the horizontal at a synchrotron. The non-dipole plane contains contributions from both the dipole interactions and non-dipole interactions such as electric quadrupole and magnetic dipole interactions.
[10] See for example O. Hemmers, R. Guillemin, E.P. Kanter, B. Krässig, D.W. Lindle, S.H. Southworth, R. Wehlitz, J. Baker, A. Hudson, M. Lotrakul, D. Rolles, W.C. Stolte, I.C. Tran, A. Wolska, S.W. Yu, M.Ya. Amusia, K.T. Cheng, L.V. Chernysheva, W.R. Johnson, S.T. Manson, Phys. Rev. Lett. 91 (2003) 053002, and references therein.
[11] The expected effect of increasing the spectrometer entrance apertures, is to decrease the background counts due to the incident light hitting the analyser entrance apertures. This increase in analyser entrance aperture also results in a decrease in the resolution (increase in peak widths) by a factor of ∼2. Although the angle-defining aperture was only increased slightly, the analyser now accepts a larger angular range of electrons in the energy-dispersive (vertical) dimension due to the increase in the entrance aperture. The magnitude of the new angular range is now sufficiently large to expect 'tails' on the low kinetic energy side of the peaks. Increasing the skimmer slit will permit

more background electrons, resulting from the inability of the spectrometer to discriminate in the horizontal plane, to pass though the spectrometer. However, this increase is small relative to the decrease in background electrons resulting from increasing the height of the analyser entrance apertures. Adding the mesh shield around the interaction region ensures the electrostatic potential at the interaction region remains constant, at ground, so the peaks should no longer shift in kinetic energy as a function of the voltages on the entrance lens.